UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

INTERPRETATION OF SCHLUMBERGER DC RESISTIVITY DATA FROM GIBSON DOME-LOCKHART BASIN STUDY AREA, SAN JUAN COUNTY, UTAH

by

Raymond D. Watts

Open File Report 82-704

1982

Abstract

A Schlumberger dc resistivity survey of the Gibson Dome-Lockhart Basin area, San Juan County, Utah, has revealed the following electrical characteristics of the area: (1) the area between the northern part of Davis Canyon and Gibson Dome is electrically quite uniform and resistive at the depth of the Pennsylvanian evaporite deposits, (2) there is a deep conductive anomaly at Horsehead Rock, and (3) there are several shallow and deep electrical anomalies in the vicinity of the Lockhart fault system. No adverse indicators were found for nuclear waste repository siting south of Indian Creek, but additional soundings should be made to increase data density and to extend the survey area southward. The Lockhart fault system appears to have triggered salt dissolution or flow outside the limits of Lockhart Basin; further geophysical work and drilling will be required to understand the origin of the Lockhart Basin structure and its present state of activity. This problem is important because geologic processes that lead to enlargement of the Lockhart Basin structure or to development of similar structures would threaten the integrity of a repository in the Gibson Dome area.

1.0 INTRODUCTION

In May and June, 1981, the U. S. Geological Survey (USGS) performed a dc resistivity survey of the Gibson Dome-Lockhart Basin area, San Juan County, Utah (fig. 1). The survey was funded by the U.S. Department of Energy (DOE) as part of DOE's program to locate a site for construction of a repository for permanent disposal of wastes from commercial nuclear power plants.

The Gibson Dome study area is part of the Paradox Basin, a physiographic region in southeastern Utah and southwestern Colorado which is underlain by salt deposits of the Paradox Member of the Hermosa Formation, which is Pennsylvanian in age. In the vicinity of Gibson Dome, in Tps. 30 and 31 S., R. 21 E., San Juan County, Utah, salt deposits in the Paradox Member ("Paradox salt") have been shown to have adequate thickness and proper burial depth for construction of a repository.

There were three objectives in performing the dc resistivity survey: (1) to determine the normal geoelectrical section for the Gibson Dome area, (2) to find whether there is a large, anomaly-free area that closely matches normal geoelectric conditions, and (3) to locate and study anomalous areas. The study of anomalous areas concentrated on Lockhart Basin, which is a structure resulting from salt dissolution and subsequent collapse of the overlying strata. The processes that formed Lockhart Basin, if they were to recur at the site of a repository during its design lifetime, would surely breach the repository. It is very important, therefore, to understand the processes that created Lockhart Basin and to attempt to predict the likelihood of their recurrence. It is equally important to explore the study area in an attempt to identify incipient Lockhart-like structures.

Forty-three (43) soundings (Schlumberger type) were obtained, covering an area of approximately 600 square kilometers (230 square miles) (fig. 2). The density of data is inadequate to define the lateral extent of anomalies in many cases. It is also inadequate to have confidence that significant anomalies have not been missed. However, the major objectives of the study have been met: information on normal geoelectric conditions for the area has been obtained, anomalies have been observed, and a largely anomaly-free area has been identified.

FIGURE 1.--Map of the Gibson Dome-Lockhart Basin study area, showing principal geographic and geologic features. Map scale is 1:250,000. Lockhart Basin is 30 km (19 mi) south-southwest of Moab, Utah.

The dotted line represents the cliff band formed by the Wingate and Kayenta Formations. Hatch Point and Harts Point are high terrain (1650-2000 m or 5400-6600 ft above sea level); Lockhart Basin and the valley of Indian Creek are low terrain (1300-1600 m or 4300-5200 ft above sea level).

Coordinates shown are kilometers in the Universal Transverse Mercator grid system, Zone 12.

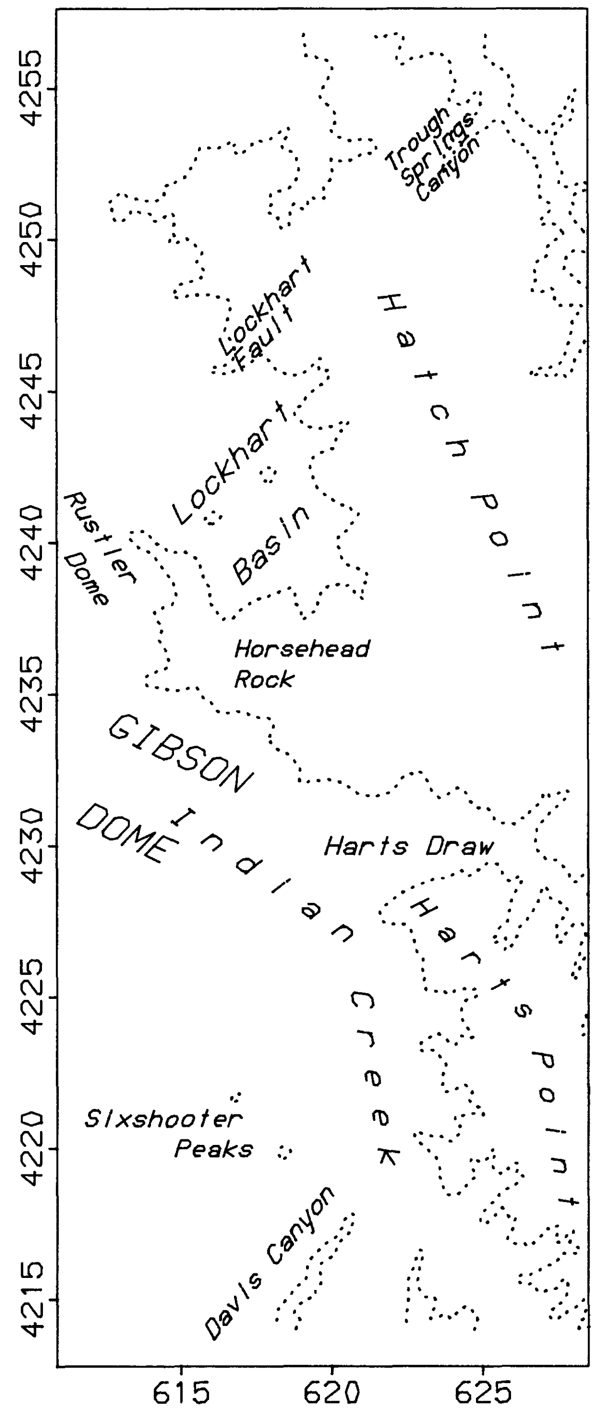
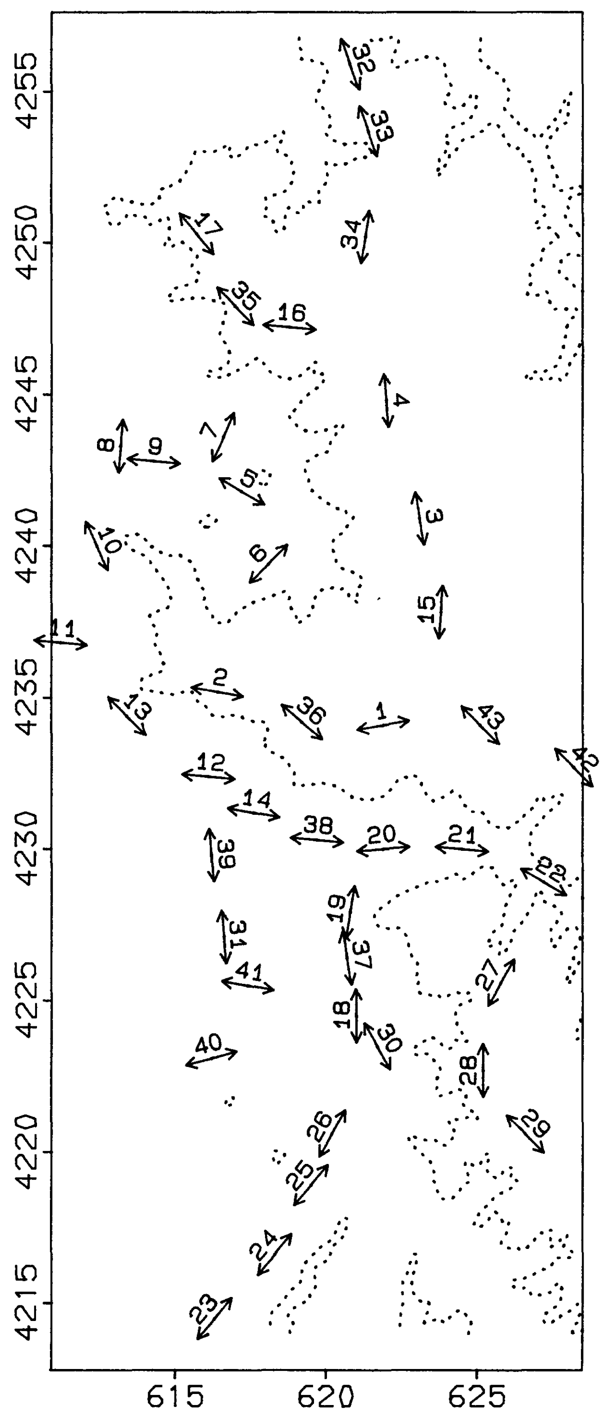


FIGURE 2.--Map of the Gibson Dome-Lockhart Basin study area, showing locations of dc resistivity sounding centers and directions of dipole spreads. Map scale is 1:250,000.

Coordinates shown are kilometers in the Universal Transverse Mercator grid system, Zone 12.



2.0 GEOLOGIC BACKGROUND

Outcropping rocks throughout most of the study area are flat-lying sediments of Permian and Mesozoic age. Gibson Dome itself is a subtle structure, expressed by maximum dips of 3 degrees at the surface. The structural closure on the dome at the surface is approximately 60 m (200 ft). There are no exposed, mapped faults in the area except around the anomalous structure of Lockhart Basin.

Lockhart Basin is a collapse feature, the result of dissolution of approximately 500 m (1600 ft) of Paradox salt. Oil-exploration drilling results (Pan American USA Charles No. 1 hole) indicate that the salt was dissolved from the top (fig. 3). The salt throughout the Paradox Basin is interbedded with dolomite, black shale, and anhydrite layers that typically constitute 20 percent of the volume of the Paradox Member. Where the salt was dissolved at Lockhart Basin, these insoluble interbeds remain as evidence of its past occurrence.

The southern part of the survey area, between Gibson Dome proper and Davis Canyon, contains the most uniform beds of salt, and is therefore the area being investigated most intensively for repository siting. The most massive salt layers occur at depths of approximately 900 m (3000 ft) below the surface, or approximately 600 m (2000 ft) above sea level.

3.0 DATA ACQUISITION AND PROCESSING

Apparent resistivities were determined and annotated on log-log sounding graphs (apparent resistivity vs. current-electrode spacing) as the soundings were made. The apparent resistivities were manually entered into a computer, which was programmed to remove discontinuities in the sounding curve, using a process described by Zohdy and others (1973). The continuous curve was fitted with a cubic spline function (Anderson, 1971), then sampled at regular logarithmic intervals for interpretation.

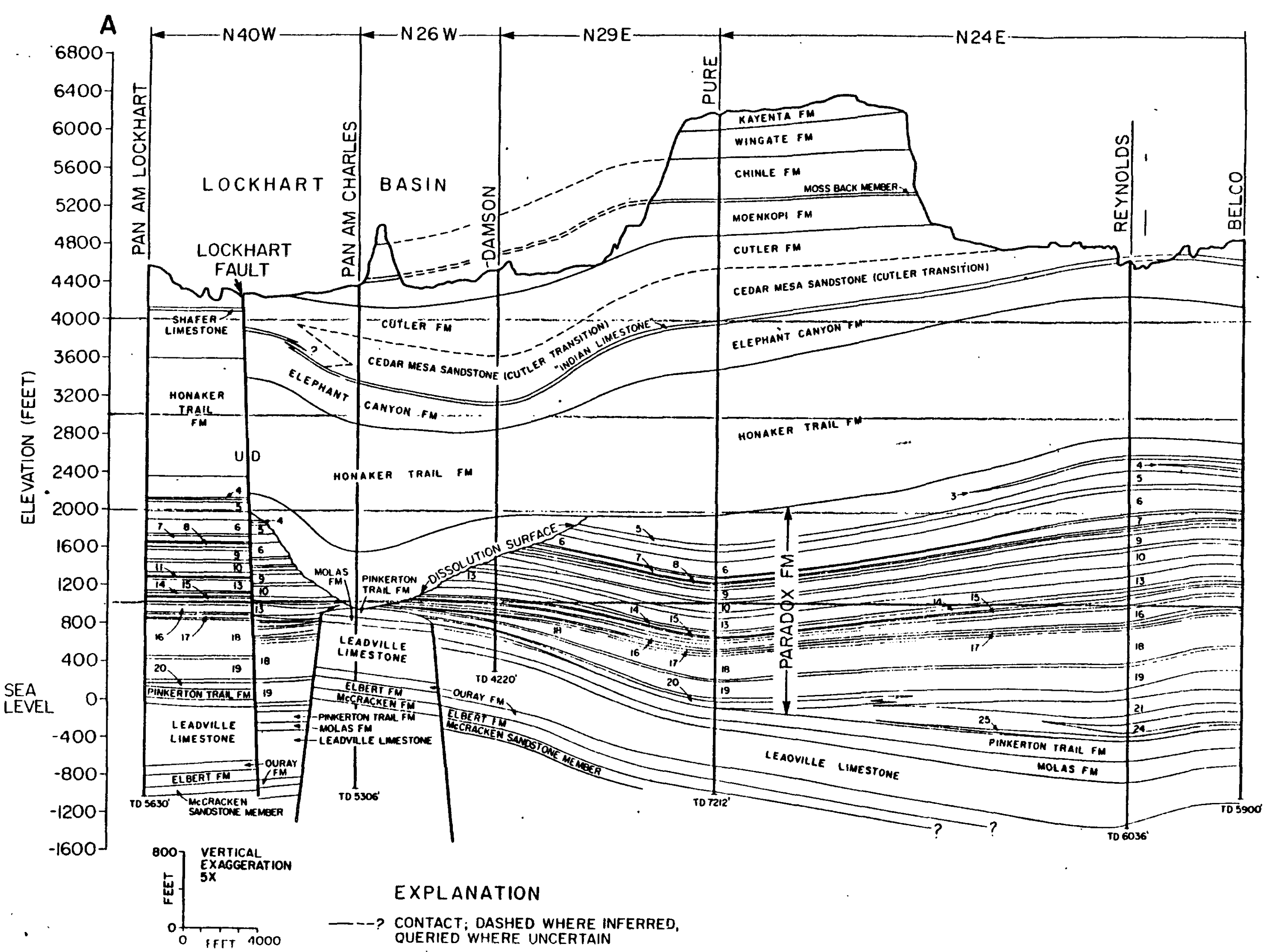
Interpretation was accomplished using the modified Dar Zarrouk method of Zohdy (1975), which infers a layered-earth model that fits the observed data. The layered-earth model was fitted with a cubic spline function passing through the logarithmic center depth of each layer. The spline function was used to interpolate resistivity at any desired depth in the section.

Several of the soundings were done on crooked roads; this practice is not ideal, but was necessary due to the limitations of travel in an area with abundant cliffs. No corrections were made for crooked-road effects. The worst

FIGURE 3.--Geologic cross section through the Gibson Dome study area. The cross section begins west of Lockhart Basin, runs eastward through the basin, then southward past Horsehead Rock and Gibson Dome.

The cross section was prepared by Jeff McCleary, Woodward-Clyde Consultants, San Francisco, California, under contract to Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, Ohio.

Scales are shown in feet (1 ft = 0.3048 m).



nonlinear soundings are estimated to involve angles of about 30 degrees, which may lead to relative errors of apparent resistivity of as much as 20 percent. Corrections can be made for the effects of crooked lines; such corrections would not be expected to alter significantly either the geoelectric structure determinations or the conclusions of this report.

Horizontal plan-view maps were prepared for four levels in the earth: 300, 600, 900, and 1200 m (1000, 2000, 3000, and 4000 ft) above sea level. This was done by subtracting the map level from the surface elevation of the center of each spread, then using the cubic spline function to determine the interpolated resistivity at that depth. The 43 points thus obtained were interpolated onto a square grid using a minimum-curvature algorithm (Webring, 1981). Figures 4 - 7 are the results of computer contouring of the gridded data.

4.0 RESULTS AND INTERPRETATION

Figures 4, 5, 6, and 7 show the interpreted resistivities at levels of 1200, 900, 600, and 300 m (4000, 3000, 2000, and 1000 ft) above sea level, respectively. These are reproduced at a scale of 1:250,000 so that they can be overlayed on a USGS 1-degree by 2-degree topographic map of the Moab quadrangle. There are also USGS geologic and structure maps of this quadrangle published at the same scale (Williams, 1964).

Figure 1 shows geographic features that are close to the locations of electrical anomalies that were discovered in this survey. Listing them from north to south in the study area, they are: (1) the Hatch Point anomaly, which lies to the north of Lockhart Basin, atop Hatch Point, near Trough Springs Canyon, (2) the Lockhart Fault anomaly, which lies just north of Lockhart Basin, also atop Hatch Point, (3) Lockhart Basin, and (4) the Horsehead Rock anomaly, which lies on the Needles Overlook and Horsehead Rock promontory of Hatch Point. Isolated anomalies that are indicated by only a single data point near the edge of the map are not discussed, since their lateral extent and importance cannot be determined using data from this survey alone.

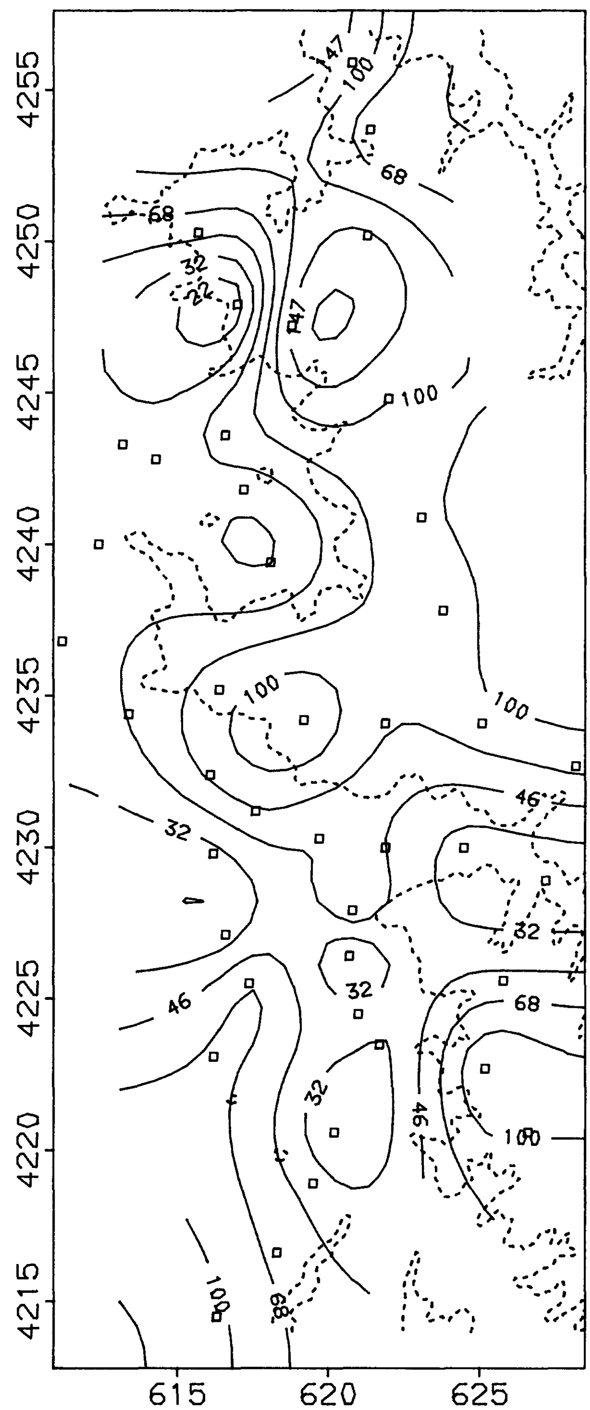
4.1 1200 m (4000 ft) Elevation

Figure 4 shows the interpreted resistivity at 1200 m (4000 ft) above sea level. This level is approximately 60 m (200 ft) beneath the surface at the lowest sounding center (in Lockhart Basin), and 800 m (2600 ft) below the surface at the highest center (on Harts Point). There is an apparent correlation between resistivity and terrain, but the

FIGURE 4.--Contour map of interpreted resistivity at the level of 1200 m (4000 ft) above sea level, in the Gibson Dome-Lockhart Basin study area, San Juan County, Utah.

Contour values are in Ohm-m. Sounding centers are indicated by small squares. The dashed line represents the Wingate-Kayenta cliff band.

Coordinate values are kilometers in the Universal Transverse Mercator (UTM) grid system, zone 12. Map scale is 1:250,000.



correlation is fortuitous. Comparison with the geologic cross section (fig. 3) allows the following resistivities to be assigned to the various formations:

Cutler/Cedar Mesa Formation		30 - 60 Ohm-m
Elephant Canyon Formation		80 - 100 Ohm-m
Honaker Trail Formation	(top)	40 Ohm-m
	(bottom)	100 Ohm-m
Paradox Formation		200 - 300 Ohm-m

The apparent correlation between terrain and resistivity is the result of the resistive Elephant Canyon Formation cutting through the 1200 m (4000 ft) elevation level near Horsehead Rock, which also happens to be an area of high terrain.

Just north of Lockhart Basin, there is an extreme gradient from the highest resistivity on the map (158 Ohm-m) to the lowest (20 Ohm-m) in less than 3 km (2 mi) of horizontal distance. The high-resistivity part of this anomaly sits astride a mapped normal fault (Williams, 1964; Hinrichs and others, 1971). This fault is part of the Lockhart fault system, which forms the northwestern border of the Lockhart Basin collapse structure. The fault, which is downdropped on the east side, displays 100 m (300 ft) of vertical offset at the north side of Lockhart Basin. The electrical anomaly is likely to be due to one or more of the following: (1) conduction within the fault zone itself due to increased water content and (or) mineralization, (2) enhanced conduction within the rocks near the fault due to a ground-water regime disturbed by the presence of the fault, or (3) a local thickening (on the west side of the anomaly) of the shaley Moenkopi Formation.

The hypothesis of locally thickened Moenkopi Formation is made credible by the recent discovery of such a feature near Trough Springs Canyon, at an oil exploration well adjacent to the same fault system (Robert Hite, USGS, oral commun., 1981). Such thickening is most readily explained by Permian or Triassic dissolution of salt, followed by structural collapse of the overlying Honaker Trail, Elephant Canyon, and Cutler Formations, then local thickening during deposition of the Moenkopi Formation. Dissolution and collapse at the site near Trough Springs Canyon must have stabilized before or during the Moenkopi deposition, or during the erosional period that is expressed as an unconformity between the Moenkopi Formation and the overlying Chinle Formation (both of Triassic age).

Determination of the true cause of the anomaly at the north edge of Lockhart Basin requires more geophysical or drilling information than is presently available. Additional electrical surveys can establish the size of the anomalous area more accurately, as well as determine whether there is an elongation of the feature in association with the Lockhart fault system.

In the southern part of the map of figure 4, there are three small anomalies with minimum resistivity values of 25 Ohm-m; these are approximately alined along the axis of the Gibson Dome structure, which the course of Indian Creek also follows. There are enough data points to affirm that the anomalies are separate. They are probably controlled by near-surface hydrologic variations resulting from zones of well-developed joints near the axis of Gibson Dome, and consequent penetration of Indian Creek's surface water into the Cutler Formation rocks. These small anomalies are not considered to be important with regard to repository siting.

4.2 900 m (3000 ft) Elevation

Figure 5 shows contoured DC resistivity values for a level of 900 m (3000 ft) above sea level. There is little apparent correlation between resistivity and terrain at this level. In the southern part of the survey area, this level is occupied by the basal part of the Honaker Trail Formation. Near Horsehead Rock, it is occupied by the upper part of the Honaker Trail Formation. In Lockhart Basin, it is occupied by the resistive Elephant Canyon Formation. To the west of Lockhart Basin, it is occupied again by the middle part of the Honaker Trail Formation (fig. 3). Observed resistivities along the cross section line shown in figure 3 are explicable entirely in terms of the formation resistivities given above in section 4.1.

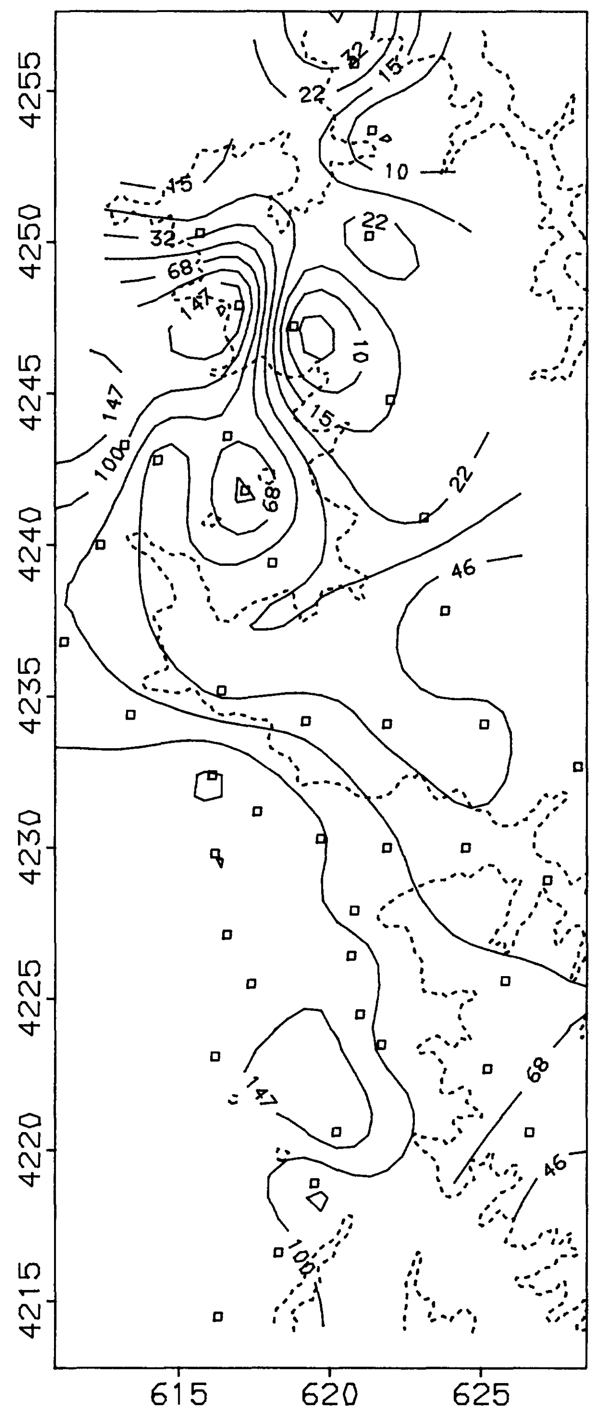
The anomaly on the north edge of Lockhart Basin that was apparent at the 1200 m (4000 ft) level in figure 4, appears again at the 900 m (3000 ft) level in figure 5, but with high and low resistivities reversed. The reversal of high and low resistivities indicates great electrical complexity in this area. At least one good conductor is certainly present, but its position is difficult to deduce because of the complexity of the data.

Farther north, on Hatch Point near Trough Springs Canyon, there is another conductive anomaly. This anomaly and the one on the north edge of Lockhart Basin have the lowest interpreted resistivities, at any level, in the entire survey. There are very few rocks that have intrinsic resistivities as low as 8 Ohm-m, so it is suspected that these low resistivities are due to saline ground-water. Because both sites are in close proximity to the Lockhart Fault system, it seems reasonable that the faults are conduits giving water access to the top of the salt formation. It is not possible to infer the present state of dis-

FIGURE 5.--Contour map of interpreted resistivity at the level of 900 m (3000 ft) above sea level, in the Gibson Dome-Lockhart Basin study area, San Juan County, Utah.

Contour values are in Ohm-m. Sounding centers are indicated by small squares. The dashed line represents the Wingate-Kayenta cliff band.

Coordinate values are kilometers in the Universal Transverse Mercator (UTM) grid system, zone 12. Map scale is 1:250,000.



solution activity based on the presence of brine.

4.3 600 and 300 m (2000 and 1000 ft) Elevations

Figure 6 shows the interpreted resistivity at 600 m (2000 ft) elevation. This level is occupied by massive salt units at Gibson Dome; corresponding high resistivities appear in figure 6. Beneath Horsehead Rock, and through Lockhart Basin up to its bounding fault system, this level is occupied by the base of the Honaker Trail Formation. To the northwest of the fault system, this level is again occupied by the evaporites of the Paradox Formation. The resistivities beneath the Needles Overlook-Horsehead Rock promontory of Hatch point are anomalously low at the 600 m (2000 ft) level.

The contour pattern at the 300 m (1000 ft) level, as shown in figure 7, is very similar. There are resistive anomalies on the southern flanks of Gibson Dome and Rustler Dome (which lies west-southwest of Lockhart Basin). The evaporite sequence is thicker in these two domes than in the surrounding areas, and resistive anomalies centered over the domes might be anticipated. The offset anomalies are not readily explained. A third resistive feature is apparent near South Sixshooter peak; it could be the electrical expression of a small, unmapped dome.

The conductive features on the 300 m (1000 ft) and 600 m (2000 ft) maps are situated in the following areas: (1) along the Lockhart fault system and in Lockhart Basin, and (2) near Horsehead Rock. These anomalies are discussed in the paragraphs below.

4.3.1 Lockhart Fault and Lockhart Basin

The anomalies along the Lockhart fault system are related to each other and to shallower anomalies in a complex way. The 50 Ohm-m conductive anomaly on Hatch point at the 300 m (1000 ft) level lies between the two conductive anomalies at the 900 m (3000 ft) level. At the intermediate level of 600 m (2000 ft), the resistivity is much more uniform through this area. This could mean that very conductive brines occur in well-defined pockets at the 900 m (3000 ft) level, then disseminate somewhat at the 600 m (2000 ft) level, and finally coalesce at an intermediate location at the 300 m (1000 ft) level. There is presently too little information to support this hypothesis with any certainty.

FIGURE 6.--Contour map of interpreted resistivity at the level of 600 m (2000 ft) above sea level, in the Gibson Dome-Lockhart Basin study area, San Juan County, Utah.

Contour values are in Ohm-m. Sounding centers are indicated by small squares. The dashed line represents the Wingate-Kayenta cliff band.

Coordinate values are kilometers in the Universal Transverse Mercator (UTM) grid system, zone 12. Map scale is 1:250,000.

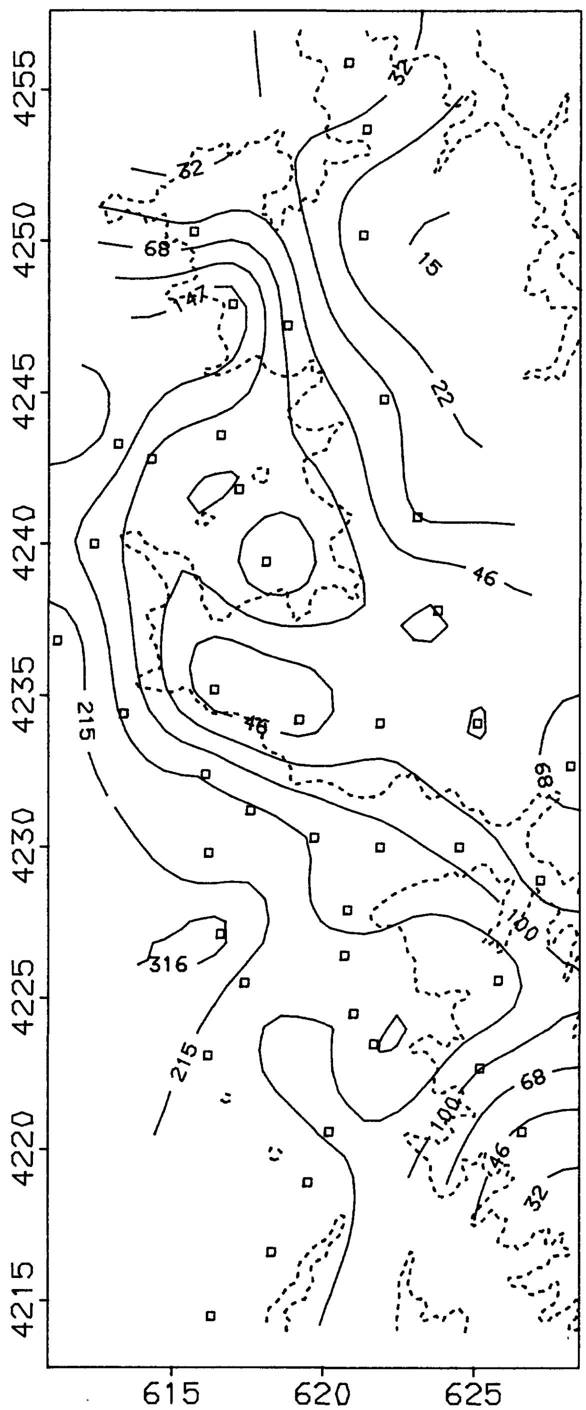
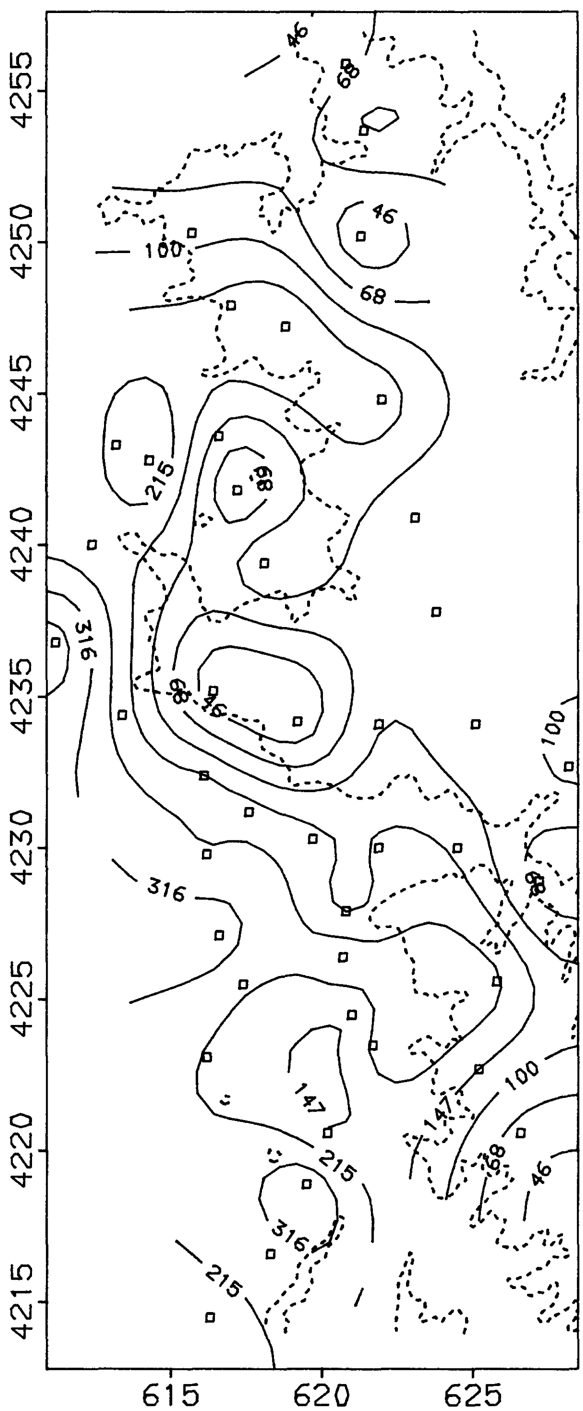


FIGURE 7.--Contour map of interpreted resistivity at the level of 300 m (1000 ft) above sea level, in the Gibson Dome-Lockhart Basin study area, San Juan County, Utah.

Contour values are in Ohm-m. Sounding centers are indicated by small squares. The dashed line represents the Wingate-Kayenta cliff band.

Coordinate values are kilometers in the Universal Transverse Mercator (UTM) grid system, zone 12. Map scale is 1:250,000.



4.3.2 Horsehead Rock

The conductive anomaly at Horsehead Rock is supported by two soundings; it is therefore considered to be a real, and significant, feature. It is most pronounced at the deepest level, 300 m (1000 ft). Oil exploration drilling results (Pure Horsehead drill hole, fig. 3) show a structural low in the Paradox Formation at this site. The most plausible explanation for the conductive electrical anomaly is the presence of brine, pooled in the low structure beneath Horsehead Rock. There is no evidence of facies changes or of structural features that could directly cause such a conductive anomaly, without the intermediate involvement of saline water.

5.0 CONCLUSIONS

The area from Davis Canyon to Gibson Dome proper, in the south part of the study area, is free of significant anomalies, especially conductive ones that could indicate the presence of brine. There are single-station, and therefore somewhat uncertain, conductive anomalies nearby, at Harts Draw and at Harts Point. There is a conductive anomaly at depth near Horsehead Rock that is probably due to brine pooled in a structural trough.

There are major anomalies near the top of the salt along the Lockhart fault system north of Lockhart Basin. This is an area of complex geology, and it is possible that the anomalies have a lithologic origin, but it is more likely that they are caused by brine.

It is somewhat surprising that Lockhart Basin itself does not possess a major, conductive electrical anomaly. Such an anomaly would be expected where resistive salt has been removed by dissolution and replaced, through structural collapse, with more conductive rock types. Saline ground-water residue might also be present, even though the dissolution and collapse may have occurred some considerable time ago. We only know that the Lockhart Basin collapse is post-Permian (that is, less than 225 million years) in age, because the Permian Cutler Formation shows very little thickening at Lockhart Basin.

The lack of a conductive anomaly at Lockhart Basin is probably due to the following three factors: (1) the salt is not dramatically more resistive than the surrounding formations, probably as a result of the occurrence of the shaley interbeds, (2) the geologic structure within the basin is very complex, so small but significant low-resistivity zones may be masked in a laterally varying environment that contains much high-resistivity material, and (3) brine may no longer be present at Lockhart Basin.

The fault system that forms the northwestern boundary of Lockhart Basin is likely to have played a role in the formation of the Basin structure. This fault system displays a dramatic anomaly at the 900 m (3000 ft) level, which is a level 200 m (650 ft) above the top of the salt. Interpreted depths of anomalies may be distorted in this region, however, because of rapid lateral variations of electrical structure. It is quite possible that this conductor is brine actually in contact with, or very close to, the top of the salt. If there is a single type of feature to look for in searching for incipient Lockhart-like structures, it would be an intense, fault-associated anomaly of this type. If such an anomaly is found, but with no surface manifestation of a fault, then extensive geophysical work should be done to determine the presence or absence of a buried fault.

The dissolution of salt at Lockhart Basin is not well understood hydrologically. Drilling information indicates that the top part of the salt has been dissolved; this presents problems for disposal of the resulting brine. Brine is denser than water, so either (a) the water and brine flowed across the top of the salt and away in an open circulation system, or (b) the brine drained downward through the salt. The most intense conductive anomalies that were discovered in this survey were along the Lockhart fault system north of the Basin, so brine may have found a conduit through the fault system. It is also possible that the deep conductive anomaly at Horsehead Rock is due to brine that drained down through Lockhart Basin itself and spread southward. Geophysical studies alone cannot answer these hydrologic questions.

6.0 RECOMMENDATIONS FOR FUTURE WORK

To assure the stability of a nuclear waste repository for a period on the order of a million years, the processes that caused the collapse at Lockhart Basin should be understood. Only with such understanding can there be confidence that another collapse of similar magnitude will not occur elsewhere in the Gibson Dome area.

The area around Lockhart Basin and its associated fault system will have to be studied intensively using methods that look at the subsurface, that is, using geophysical methods and drilling. The geology of outcropping rocks is deceptively simple outside the limits of Lockhart Basin proper. Considerable basement movement may have taken place with little consequential disruption of the near-surface rocks. Salt dissolution or flow mobilization due to basement tectonic processes may have resulted in depressions that were in-filled or topographic highs that were draped during subsequent sedimentary depositional periods. There may be little or no surficial expression of these complex geologic processes, which is the case at the recently discovered zone of thickened Moenkopi Formation near Trough Springs Canyon.

In places where ancient salt mobilization resulted in thickness variations in the salt and subsequently in the overlying sediments, a three-element geophysical exploration scheme should be used. Gravity surveys are sensitive to variations in thickness of salt, because of salt's low density. Electrical methods are sensitive to variations between certain types of lithology (usually being able to distinguish salt, sandstone, and shale), and can therefore be used to study thickness variations in the sediments above the salt. Seismic methods have resolution that cannot be matched by gravity or electrical methods, but are much more expensive. Interesting and anomalous areas that have been identified gravitationally and electrically can be studied in detail seismically without excessive expense. Drilling, of course, offers the best look at a vertical column through interesting places that have been identified geophysically. The amount of information obtained in a drilling program will be optimized if the holes are used for borehole geophysical experiments, which dramatically extend the volume of explored rock.

The survey described in this report has left some specific questions unanswered, that can be answered with more electrical work. The lateral extents of the anomalies near the Lockhart fault system should be determined more precisely, in order to determine the likely size of present-day brine zones. Audio-frequency magnetotelluric soundings and telluric profiles would be especially useful because of their good lateral resolution. More Schlumberger soundings would be useful as control points for the magnetotellurics as well as to gain confidence that no anomalies have been missed.

Additional Schlumberger soundings are needed to the east and south of the area considered in this report. The deep, single-station anomalies at Harts Point and Harts Draw may be related only to general trends in geoelectric conditions; on the other hand, they might be isolated anomalies resulting from local hydrologic or structural conditions. Additional data to the east would resolve this question. Additional data to the south are required simply to encompass the proposed repository sites.

7.0 ACKNOWLEDGEMENTS

The high quality of the data presented in this report are due to the experience and ability of Robert Bisdorf and his field crew: Dean Shoenthaler, Matt Powers, and Don McNair. Adel Zohdy and Robert Bisdorf supplied the computer programs that determined earth resistivity from measured apparent resistivity. Michael Webring supplied the program that grids data for contouring. Cindy Cooper, of Electronic Data Systems, was instrumental in getting the graphics programs working on USGS' new DEC VAX-11/780 computer. Torrin Warrender participated in the data acquisition and performed almost all the computer and graphics processing. Bob Hite provided invaluable geological insight, without which the interpretation of the data would have been impossible.

8.0 REFERENCES

Anderson, W.L., 1971, Application of bicubic spline functions to two-dimensional gridded data: Report P13-203579, National Technical Information Service (NTIS), Springfield, Virginia.

Hinrichs, E.N., Krummel, W.J., Jr., Connor, J.J., and Moore, H.J. II, 1971, Geologic map of the southwest quarter of the Hatch Point quadrangle, San Juan County, Utah: U.S.G.S. Miscellaneous Geologic Investigations Map I-670.

Webring, M., 1981, MINC -- a gridding program based on minimum curvature: U.S.G.S. Open File Report 81-1224, 11 p, 2 appendices.

Williams, P.L., 1964, Geology, structure, and uranium deposits of the Moab quadrangle, Colorado and Utah: U.S.G.S. Miscellaneous Geologic Investigations Map I-360.

Zohdy, A.A.R., Anderson, L.A., and Muffler, L.J.P.,1973, resistivity, self potential, and induced polarization surveys of a vapor dominated system: Geophysics, Vol 38, p 1130-1144.

Zohdy, A.A.R., 1975, Automatic interpretation of Schlumberger sounding curves using modified Dar Zarrouk functions: U.S.G.S. Bulletin 1313-E, 39 p.